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Harvest Weed Seed Control: Seed Production and Retention of *Fallopia convolvulus*, *Sinapis arvensis*, *Spergula arvensis* and *Stellaria media* at Spring Oat Maturity

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Abstract: If seeds retained on weeds at crop harvest could be collected and removed by the combine harvester, weed infestation could be reduced in the following years. We estimated the proportion of weed seeds that could be removed at oat harvest. The seed production and shedding pattern of *Fallopia convolvulus*, *Sinapis arvensis*, *Spergula arvensis* and *Stellaria media*, were assessed in two spring oat fields in Denmark during 2018 and 2019. Ten randomly chosen plants of each species were surrounded by a porous net before flowering. The start time of seed shedding was recorded, and the seeds were collected from the nets and counted weekly until oat harvest. Just before harvest, the retained seeds on the weed plants were counted. The ratio between harvestable seeds and shed seeds during the growing season was determined. On average 260, 195, 411 and 316 seeds plant^{-1} were produced by *F. convolvulus*, *Sinapis arvensis*, *Spergula arvensis* and *S. media*, respectively, of which in average 44%, 67%, 45% and 56% of the seeds were retained on the plants at harvest. There was a strong, positive correlation between the weed biomass and the total seed production.

Keywords: HWSC; seed shedding; soil seed bank; spring cereals

1. Introduction

Black bindweed (*Fallopia convolvulus* (L.) Á. Löve), wild mustard (*Sinapis arvensis* L.), chickweed (*Stellaria media* (L.) Vill.) and corn spurrey (*Spergula arvensis* L.) are four common weed species in cereal fields in Scandinavia. Based on the Danish weed surveys in 1987–1989 and 2001–2004, *F. convolvulus* and *S. media* were among the dominant weed species with a frequency higher than 10% in all fields. *Spergula arvensis* and *Sinapis arvensis* became even more frequent in some crops from 1987–1988 to 2001–2004 [1].

Fallopia convolvulus is one of the most troublesome weeds in the world in cereal fields [2]. The climbing habit of the plant allows it to obtain sunlight while growing in stands of grain or other tall crops that may otherwise shade it [3]. The growth of *F. convolvulus* shoots is positively correlated with the daily temperature curve. However, as days become successively warmer, growth is successively less [4]. A single plant that emerges early in the growing season (April) may produce as many as 30,000 seeds, while individuals emerging two months later (June) may produce 15,000 seeds [2]. *Fallopia convolvulus* has an indeterminate flowering habit, which can result in flowers, immature seeds and mature seeds present on the same plant [3].

Sinapis arvensis is widely introduced and naturalized in temperate regions around the world. It has a persistent seed bank, a competitive annual growth habit and high fecundity; all characteristics contribute to its weedy nature, and ensure that it will remain a problem. During harvest operations, pods shatter readily, and some seeds are harvested with the crop [5]. *Sinapis arvensis* flowers six weeks after emergence with the peak in June and July in northern latitudes, but it can continue flowering until the frost starts [6]. The average number of seeds plant^{-1} reported for plants grown without competition varied from 2000 to 3500 [7], and in dense plant populations, from 10 to 590 [8]. Seed longevity of up to 75 years has been reported [7].

Stellaria media is native to Europe, and exists as one of the most distributed weeds in the world. It is one of the most common weeds in spring and winter cereals in northern Europe. It quickly colonizes disturbed fields [9], but it is considered as a weak competitor [10]. The number of seeds plant^{-1} has been reported to be in the range of 500 [11] to 2500 [12]. It has numerous, small, easily dispersed seeds, and can flower and set seed throughout the year [13].

Spergula arvensis is a weed of cereals in almost all areas of the world. The plant flowers from June to November and will shatter mature seeds from July onward. Flowering and seeding continue until the plant dies. A large plant may have 500 capsules and releases 7500 seeds. Capsules produced early in the season may contain 25 seeds, but later capsules may only contain five [2].

Sinapis arvensis and *Spergula arvensis* can only reproduce by seeds, while *F. convolvulus* and *S. media* also can reproduce by creeping roots and creeping stems rooting at the nodes, respectively [14]. The soil seed bank is the primary source of weed infestations. Thus, information on their seed production and shedding pattern is necessary for applying proper weed management strategies. Weed seeds disperse when the seeds ripen, detach and fall to the ground [15]. Late season production of weed seeds has gained particular attention because of the development of herbicide-resistant weeds [16]. Most farmers adopt weed management programs that are efficient in controlling weeds and preventing weed seed production [17]. At harvest, weed seed control provides an opportunity to collect and destroy weed seeds before their return to the soil seed bank [18]. Chaff carts, narrow windrow burning, bale direct, chaff tramlining and use of the Harrington seed destructor are Harvest Weed Seed Control (HWSC) systems used to collect and/or kill weed seeds at harvest [19–21]. Seed shattering before harvest ensures that seeds escape control at crop harvest, and thereby persist within the field [15]. The amount of weed seeds shattered before harvest varies among weed species, and is influenced by environmental conditions and agronomic factors [22,23]. The effect of HWSC methods depends on the seed retention of the target species [23] and canopy height at which the weed seeds are retained relative to crop harvest height [24].

The objective of this study was to evaluate the seed production, shedding and retention of four of the most common weed species in conventional and organic oat fields in Denmark. We assessed the potential to harvest their seeds during grain harvest by a combine harvester as a weed seed control strategy to reduce the fresh seed input to the soil seed bank. We hypothesized that a significant fraction of their seeds potentially could be collected and removed from the field during crop harvesting.

2. Materials and Methods

We assessed the seed shattering and seed production of *Fallopia convolvulus*, *Sinapis arvensis*, *Spergula arvensis* and *Stellaria media* during the growing season of spring oat in two fields with sandy soil at the research station in Taastrup (55°38′ N, 12°17′ E), Denmark. The fields were ploughed in the spring and harrowed before sowing. One field was sown 19 April and harvested 2 August 2018 and the other field was sown 2 April and harvested 23 August 2019. The oat cultivar was Dominik and Symphony in 2018 and 2019, respectively, with the sowing rate of 170 and 175 kg ha^{-1}. No pesticide or fertilizer was applied both years on the study.

Ten plants of each species were selected randomly and surrounded by a trap comprised of a porous net (precision woven open mesh fabrics: SEFAR NITEX 06-475/56, Sefar, Germany; mesh opening: 475 µm—opening area: 56%) before flowering covering an area of approximate 710 cm^2 (Figure 1). Traps were checked each week to record the start time of seeds shedding. Hereafter, seeds were collected using a portable vacuum cleaner every 6–8 days, depending on weather conditions, and stored in paper bags. The collected seeds were counted until oat harvest. Just before crop harvest, weed plants were cut at the soil surface, and the number of seeds retained on the weed plants was counted. The ratio of harvestable seeds to seeds produced by each weed species was determined.

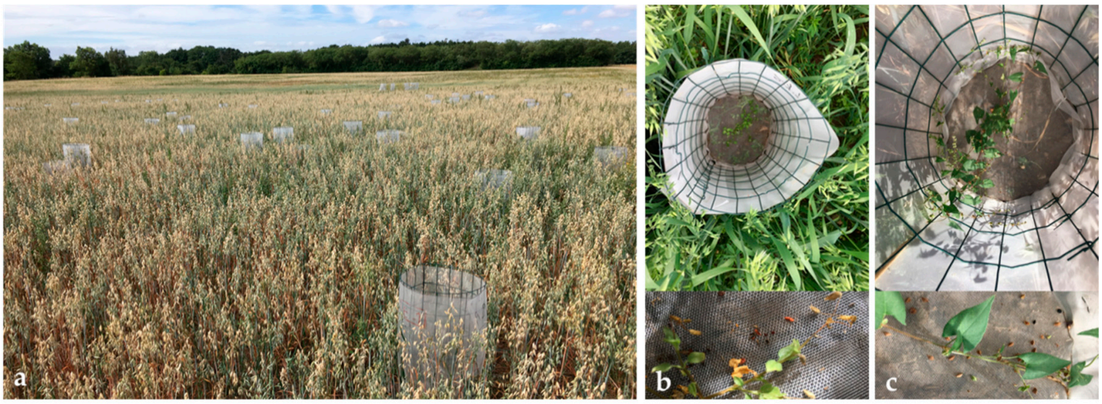

Figure 1. (**a**) Seed traps in the oat field in 2018. Maturing plants and shattered seeds of (**b**) *Stellaria media* and (**c**) *Fallopia convolvulus* in traps in 2019.

Weather data was provided from the research weather station in the area (55°67′ N, 12°30′ E) (Figure 2). Daily maximum and minimum temperature data were used to calculate the Growing Degree Days (GDD) for the growing seasons:

$$GDD = \sum_{S1}^{S2} (Tm - b_0) \tag{1}$$

where Tm and b_0 represent the mean daily temperature and the base temperature (0 °C), respectively. $S1$ and $S2$ are the time of crop sowing and harvesting, respectively.

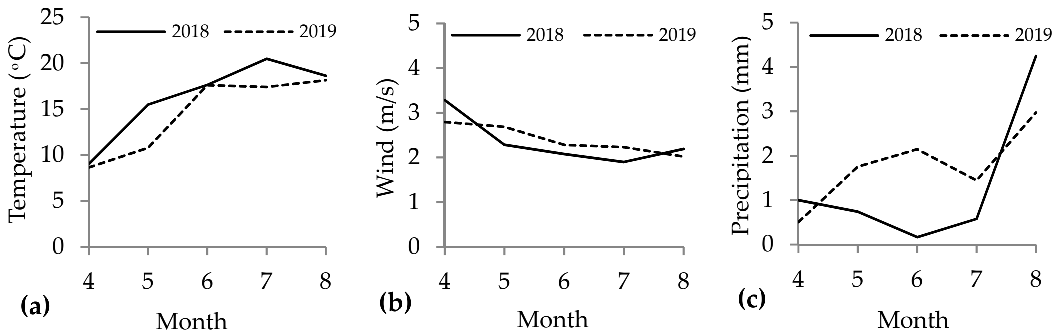

Figure 2. Weather data during the experiments: (**a**) temperature, (**b**) wind and (**c**) precipitation. Measurement height: 2, 2 and 1.5 m above ground level for temperature, wind and precipitation, respectively.

To test whether the total seed production and dry weight of the plants varied significantly between the years, analysis of variance (ANOVA) followed by Fisher's least significant difference (LSD) for means separation was done using R version 3.6.1 [25]. Variance homogeneity was assessed by visual inspection of residual plots. To test whether seed shed differed between the weeks for each species, repeated measurement was used. The analyses were done using the extension packages *lme4* [26] and *multcomp* [27]. Plants were considered as random effect, and the number of shattered seeds over the weeks considered as the response. The significance level was set to 0.05. The relationship between weed seed production and biomass was assessed using linear regression analysis.

3. Results

3.1. Seed Production and Shedding in 2018

Figures 3–5 show the seed shedding pattern of *F. convolvulus*, *Sinapis arvensis* and *Spergula arvensis*, respectively. All three species started seed shedding more than one week before oat harvest in 2018. *Fallopia convolvulus* started to shed seeds between 12–19 July, and the largest number of shed seeds took place in the week before harvest (26 July–1 August) (Figure 3a). Seed shedding of *Sinapis arvensis* started between 20–27 July. The largest number of seeds was shed between 27 July–2 August, one week before harvest (Figure 4a). *Spergula arvensis* started seed shedding between 26 June–3 July, and the greatest number of shed seeds took place between 9–16 July (Figure 5a). On average 200, 109 and 697 seeds plant^{-1} were produced by *F. convolvulus*, *Sinapis arvensis* and *Spergula arvensis*, respectively, of which 57.5%, 27.7% and 39.0% of the seeds were shed before harvest. The difference between the weekly numbers of shed seeds for these three species was statistically significant (p = 0.001).

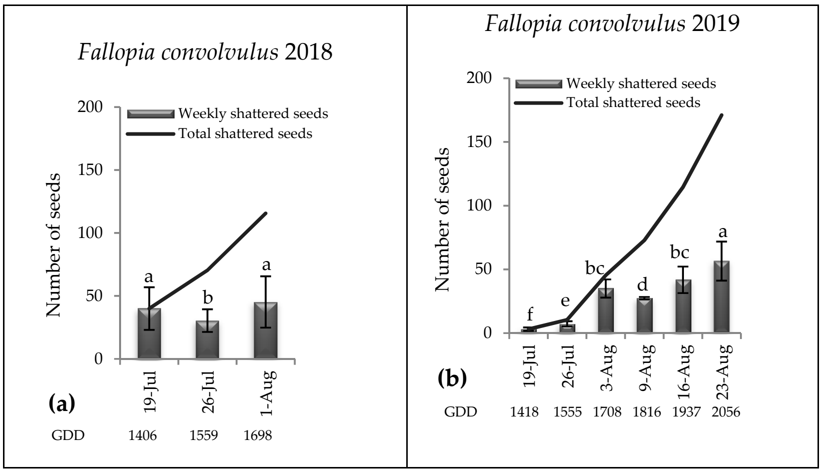

Figure 3. Average weekly and cumulative seed shedding per plant of *Fallopia convolvulus* in (**a**) 2018 and (**b**) 2019 during the growing season of spring oat. GDD = Growth Degree Days = sum of daily mean temperatures above 0 from the date the oat was sown**.** Columns with different letters are statistically different at the 0.05 probability level.

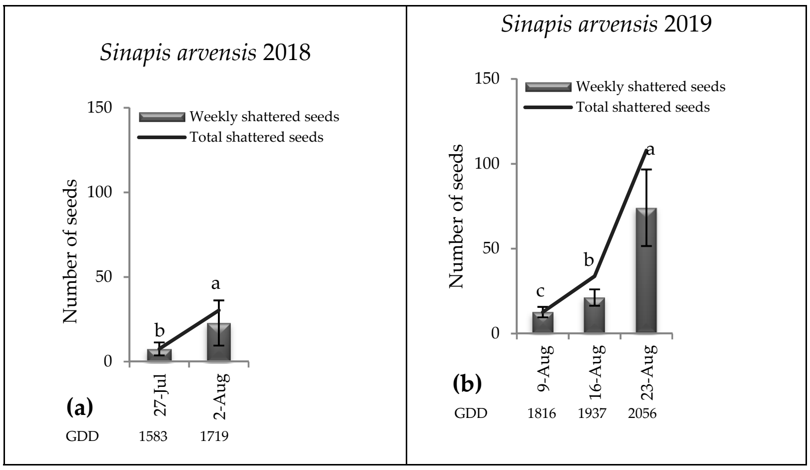

Figure 4. Average weekly and cumulative seed shedding per plant of *Sinapis arvensis* in (**a**) 2018 and (**b**) 2019 during the growing season of spring oat. GDD = Growth Degree Days = sum of daily mean temperatures above 0 from the date the oat was sown**.** Columns with different letters are statistically different at the 0.05 probability level.

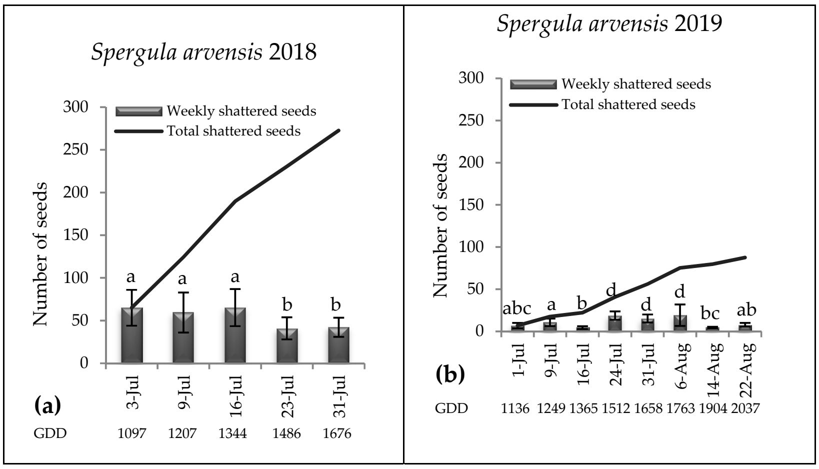

Figure 5. Average weekly and cumulative seed shedding per plant of *Spergula arvensis* in (**a**) 2018 and (**b**) 2019 during the growing season of spring oat. GDD = Growth Degree Days = sum of daily mean temperatures above 0 from the date the oat was sown**.** Columns with different letters are statistically different at the 0.05 probability level.

Seeds of *S. media* started to shatter one week before harvest (26 July–2 August) (Figure 6a). *Stellaria media* produced on average 52 seeds plant^{-1}, of which 16.2% were shattered before harvest.

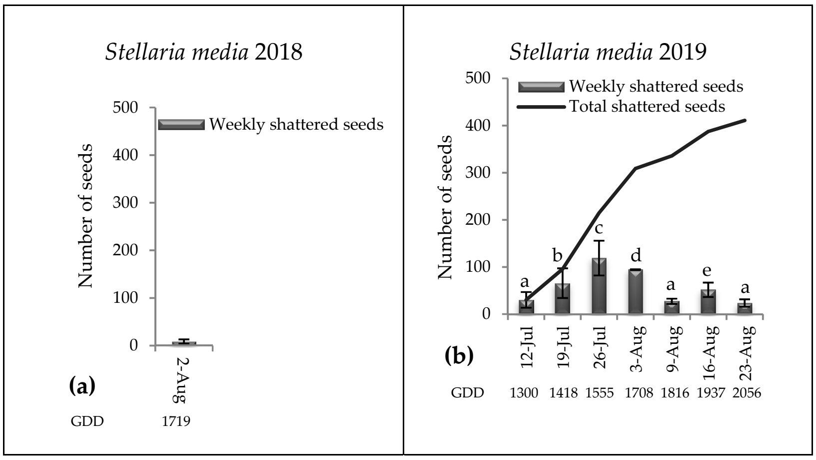

Figure 6. Average weekly and cumulative seed shedding per plant of *Stellaria media* in (**a**) 2018 and (**b**) 2019 during the growing season of spring oat. GDD = Growth Degree Days = sum of daily mean temperatures above 0 from the date the oat was sown. Columns with different letters are statistically different at the 0.05 probability level.

3.2. Seed Production and Shedding in 2019

All four species started seed shedding more than one week before oat harvest in 2019. *Fallopia convolvulus* started to shed seeds between 12–19 July, and the largest number of shed seeds took place the week before harvest (16–23 August) (Figure 3b). Seed shedding of *Sinapis arvensis* started between 2–9 August. The greatest number of seeds was shed between 16−23 August, also one week before harvest (Figure 4b). *Spergula arvensis* started seed shedding between 24 June–1 July, and the largest number of shed seeds took place between 31 July–6 August (Figure 5b). Seed shedding of *S. media* started between 5–12 July. The largest number of seeds was shed between 19–26 July (Figure 6b). On average 321, 282, 125 and 580 seeds plant^{-1} were produced by *F. convolvulus*, *Sinapis arvensis*, *Spergula arvensis* and *S. media*, respectively, of which 53.2%, 38.1%, 69.5% and 70.7% of the seeds were shed before harvest. The difference between the weekly numbers of shed seeds for all four species was statistically significant ($p = 0.001$).

Seed production was significantly different between the years for *Spergula arvensis* ($p = 0.0056$), *Sinapis arvensis* ($p = 0.03$) and *S. media* ($p = 0.0016$), but not for *F. convolvulus* ($p = 0.25$).

3.3. Plant Dry Weight

The average plant dry weight at crop harvest was only different between the years for *Spergula arvensis* (1.03 g in 2018; 0.28 g in 2019; $p \leq 0.002$). The average plant dry weight at crop harvest for *F. convolvulus*, *Sinapis arvensis* and *S. media* was 1.6, 0.8 and 4.8 g, respectively.

For all species, there was a positive correlation between weed plant dry weight and total seed production (Figure 7).

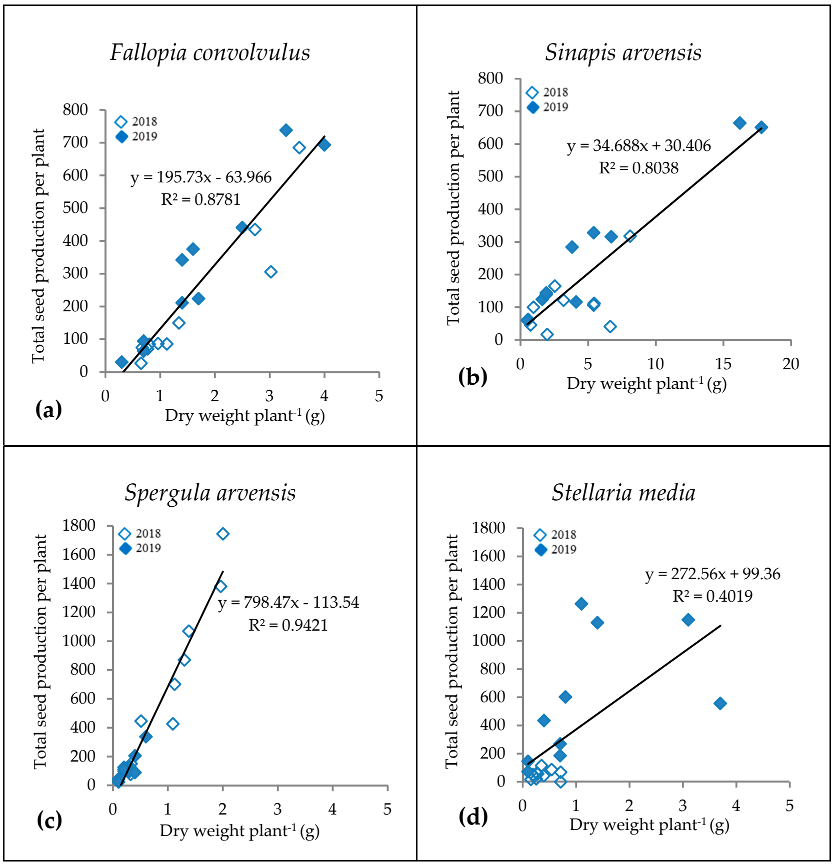

Figure 7. Total seed production per plant of (**a**) *Fallopia convolvulus*, (**b**) *Sinapis arvensis*, (**c**) *Spergula arvensis* and (**d**) *Stellaria media* as a function of the plant dry weight in 2018 and 2019.

4. Discussion

A high fraction of weed seed retained on the weed plants at harvest increases the potential for HWSC methods. We determined both the amounts of shed seeds and the retained seeds on the weeds to find the potentially harvestable ratio. The weed species showed different patterns in seed production and shedding, which also varied between the years. Different weather conditions characterized the two growing seasons. In 2018, the summer was unusually dry, warm and sunny, with many days having temperatures greater than 30 °C. It was the warmest summer since 1874 [28]. The oat plants became drought-stressed, resulting in less growth and a thinner oat stand, creating more space and light for the weeds. In the dry and warm weather in 2018, weeds and crop plants matured earlier than in 2019, resulting in a three weeks earlier harvest. In the dry season, the dry weight of *F. convolvulus*, *Sinapis arvensis* and *S. media* decreased by 68.3%, 40.8% and 11.3%, and the total seed production decreased by 90.9%, 61.3% and 37.5%, respectively.

In field trials in the United Kingdom, Wright et al. [29] evaluated the influence of two different soil moisture regimes on the competitive ability of *Sinapis arvensis* in spring wheat. Under dry conditions, the competitiveness of *Sinapis arvensis* measured as plant dry weight and seed production was significantly reduced. The dry weight and total seed production of *Spergula arvensis* increased by 72.9% and 81.9% in 2018 compared to the rainy season in 2019, as it was a rather weak competitor to oat [10].

On average, 195 seeds were produced by each plant of *Sinapis arvensis* in the two years. Forcella et al. [30] estimated the total viable seed production of *Sinapis arvensis* to be 2475 seeds m^{-2} in corn fields in two years. Seeds were completely dispersed before corn harvest in the warmest year, whereas in the cold year, one-third of seeds were retained on the plant and dispersed via combines during harvest [30]. Matured pods of *Sinapis arvensis* usually remain intact until the crop is harvested. During harvesting operations, seeds fall in the vicinity of the parent plants, or are most likely gathered with the crop seeds and afterwards spread with the chaff within the field during the harvesting operation [5,7]. We recorded that seeds started to shatter at 1583 GDD in the first year and 1816 GDD in the second year. Before harvest, 27.7% and 38.1% of the seeds were shed, while Burton et al. [31] reported that seed shatter of *Sinapis arvensis* began at 1110 GDD in spring wheat in 2015 in Saskatchewan, Canada. Only 10.6% of the total seed production of *Sinapis arvensis* shattered before harvest.

During the growing seasons, *F. convolvulus* climbs upwards, twining around the crop plants and in the case of cereals, it can cause lodging and make combine harvesting difficult [2]. Seeds started to shatter almost at the same period both years (1406 and 1418 GDD in 2018 and 2019, respectively) and almost with the same amount of seed shatter. Before harvest, 57.5% and 53.2% of seed shed. Burton et al. [31] reported from Saskatchewan, Canada, that seed shatter of *F. convolvulus* began at 1120 GDD in spring wheat in 2014 and 1060 GDD in 2015. They have observed a considerable variation in the seed shatter of *F. convolvulus* between the two years (31% of seed shattered before harvest in 2014 and 4.7% in 2015). They found that the high percentage of seed shattering in 2014 was caused by the dry conditions with periods of wind gusts close to the harvest time. However, we only observe a small variation in the seed shattering patterns. In both years, about 50% of the seed shed happened before harvest, but the total seed production was significantly reduced in the dry season. Dosland and Arnold [32] found that the supply of soil moisture was an essential factor for the competition between *F. convolvulus* and cereals. In a year with low precipitation, the weed germinated earlier and developed leaf area and dry weight, rapidly contributing to the early depletion of water in the field. The growth of the crop proceeded slowly, and there was an early loss of leaf area at heading time, resulting in a reduced yield [32].

There is limited information on seed retention and the possibility of harvesting *Spergula arvensis* and *S. media* seeds by a combine harvester. On average, 411 and 316 seeds were produced by *Spergula arvensis* and *S. media* in the two years, respectively, of which 45% and 56% was retained on the plants at harvest. In the dry season (2018), *S. media* started to shed seeds at 1559 GDD, while in the rainy year (2019), shattering started at 1300 GDD with 16.2% and 70.7% of seeds shed before harvest, respectively. *Spergula arvensis* started to shed seeds at 1097 and 1136 GDD in 2018 and 2019, respectively, with 39.0% and 69.5% of seeds shed before harvest. Tidemann et al. [33] reported that seed retention decreased as GDD increased. Seed retention over time varies by species, site, year and treatment. Many factors may contribute to the variation in seed retention of a plant species such as soil condition, drought, thunderstorm, wind, rainfall and competition between plants, and variation between biotypes [33].

The efficiency of HWSC relies on the proportion of the weed seed production that is retained at crop maturity [34]. Seed retention higher than 80% at crop maturity happens for many agronomically important weed species creating a unique opportunity to target these weed seeds and prevent them from becoming a part of the weed seed bank in the soil [34]. Delays in crop harvest can result in fewer weed seeds being captured because of a higher rate of seed shatter [35,36].

Fifteen cm reflects the practical harvest height for many growers. This height does not ensure that a large fraction of retained seeds on the weeds can be harvested for all the weed species. *Sinapis arvensis* is a tall plant (30–60 cm) with erect branching stems [14], making it possible to harvest the retained seeds by a combine harvester. This is also possible for *Spergula arvensis* (15–40 cm), which also has ascending or erect stems [14]. The stem of *F. convolvulus* (height: up to 2 m) is prostrate, but climbs the stems of other plants [14], which also make it possible to harvest retained seeds. However, *S. media*, which may become 20–60 cm tall, has decumbent to erect stems [14], which may make it difficult to collect a large proportion of the retained seeds at crop harvest. It is also likely that some seeds spread and fall to the soil surface during the harvesting process.

We observed a strong positive correlation between the weed biomass and the total seed production. The larger the plant, the more seeds were produced [37]. Schwartz et al. [37] also reported a strong correlation between the weed biomass and total seed production of *Amaranthus tuberculatus* and *A. palmeri* in soybean fields. A strong correlation between biomass production and seed production has been documented for many weed species [38–41]. Regardless of the species, the majority of smaller plants had low seed production, indicating that these plants were late-emerging cohorts [42].

We have now shown that a large proportion of seeds produced during the growing season of common weed species potentially can be collected and removed or destroyed [43–45] by a combine harvester at crop harvest. The next step will be to test how large a fraction of this potential a combine harvest actually collects, as it depends on several factors such as harvest height and the number of seeds dropping to the soil surface under the harvesting process.

Author Contributions: C.A. was responsible for funding acquisition and the design of the experiment. Z.B. conducted the practical work, data processing and wrote the first draft of the manuscript. Both authors reviewed, edited and accepted the final manuscript. All authors have read and agreed to the published version of the manuscript.

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